Search for BSM Higgs bosons at CMS

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DESY

On behalf of the **CMS** Collaboration

HELMHOLTZ ASSOCIATION

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Motivation for the BSM Higgs searches

- Various **indications** for the physics **Beyond Standard Model** (BSM)
- Natural to look for New Physics!

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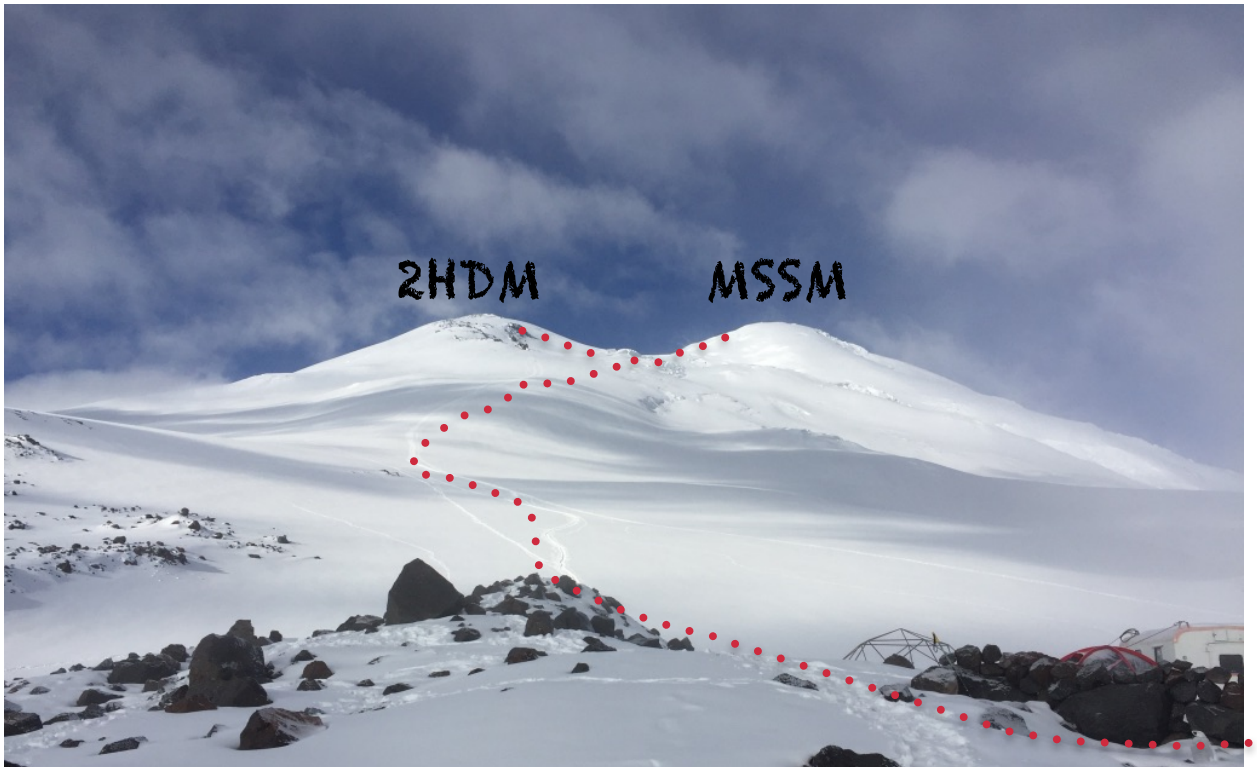
- Various **indications** for the physics **Beyond Standard Model** (BSM)
- Natural to look for New Physics!
- **h(125)** can be the **first member** of an **Extended Higgs Sector**:
  - as predicted by several **BSM** extensions
  - direct searches for **additional Higgs** bosons



2HDM and MSSM

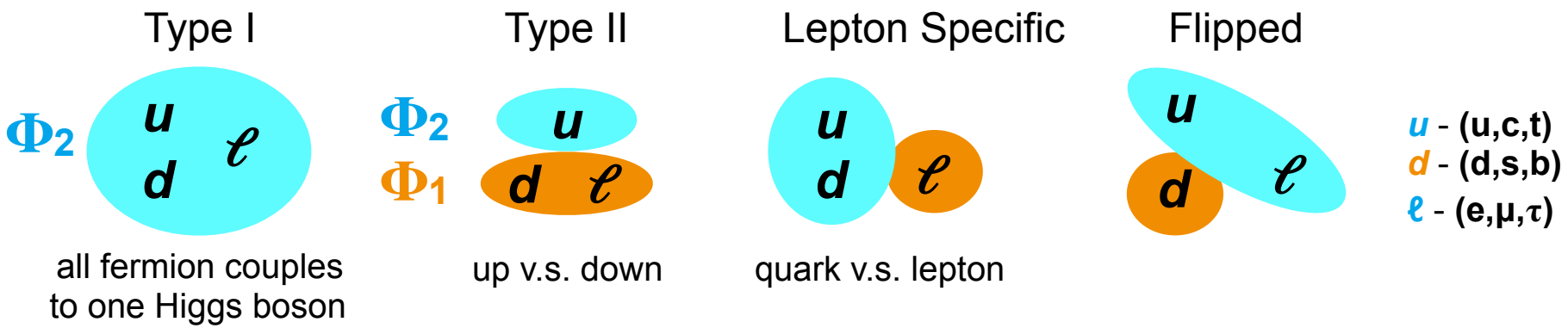
- Higgs sector of **Two Higgs Doublet Model** (2HDM):

2 doublets		CP-even	CP-odd	Charged
Φ_2	Φ_1	h, H	A	$H^{\pm}$

(h, H, A) ≡ ϕ

- **tan β** - ratio of vacuum expectation values ; **α** - **mixing** angle between h and H

- **4 types of 2HDM** with natural flavour and CP conservation, depending on how the 2 Higgs doublet fields couple to SM particles



all fermion couples to one Higgs boson

up v.s. down

quark v.s. lepton

- **Minimal Supersymmetric Standard Model** (MSSM) features same Higgs sector structure as in Type II:
  - **Two parameters at tree-level: m_A and tanβ**

2HDM and MSSM

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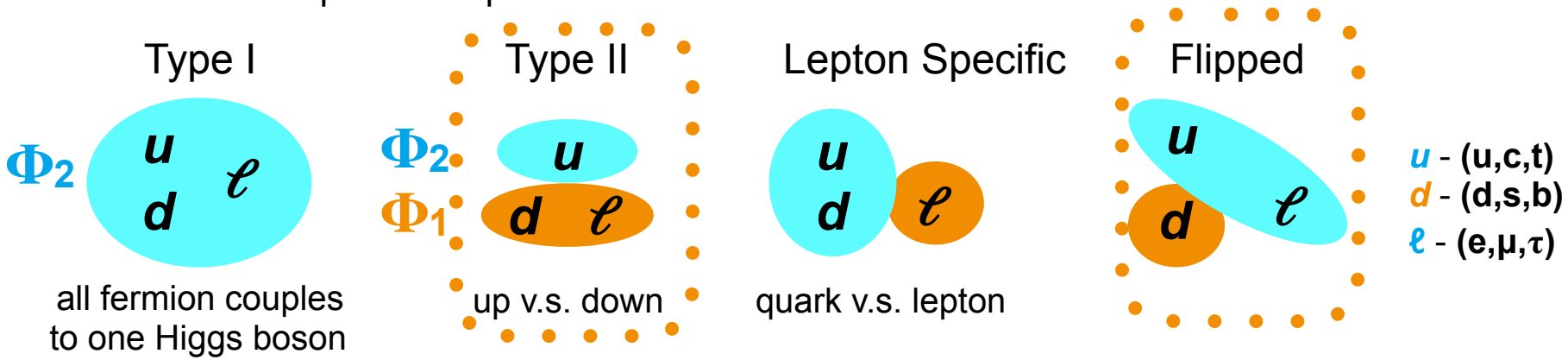


Minimal Supersymmetric Standard Model (MSSM) features same Higgs sector structure as in Type II:

Two parameters at tree-level: m_A and tanβ

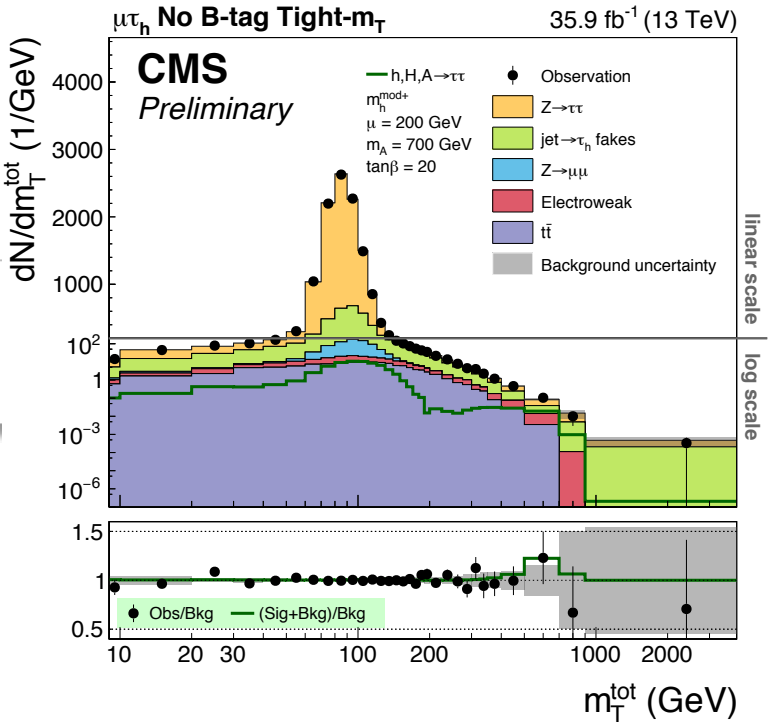
MSSM h/H/A→ττ

CMS-PAS-HIG-17-020

- Search for MSSM ϕ(h/H/A)→ττ:
  - Second largest BR
  - Clean final state
  - Manageable backgrounds
- Consider 2 production mechanisms:
  - gluon fusion, dominant at low tanβ
  - b-associated, dominant at large tanβ
- 4 main ττ decays: eτ, μτh, eμ and τhτh
- 16 categorise to optimise sensitivity
- Largely data-driven background estimation
- Signal extraction observable:

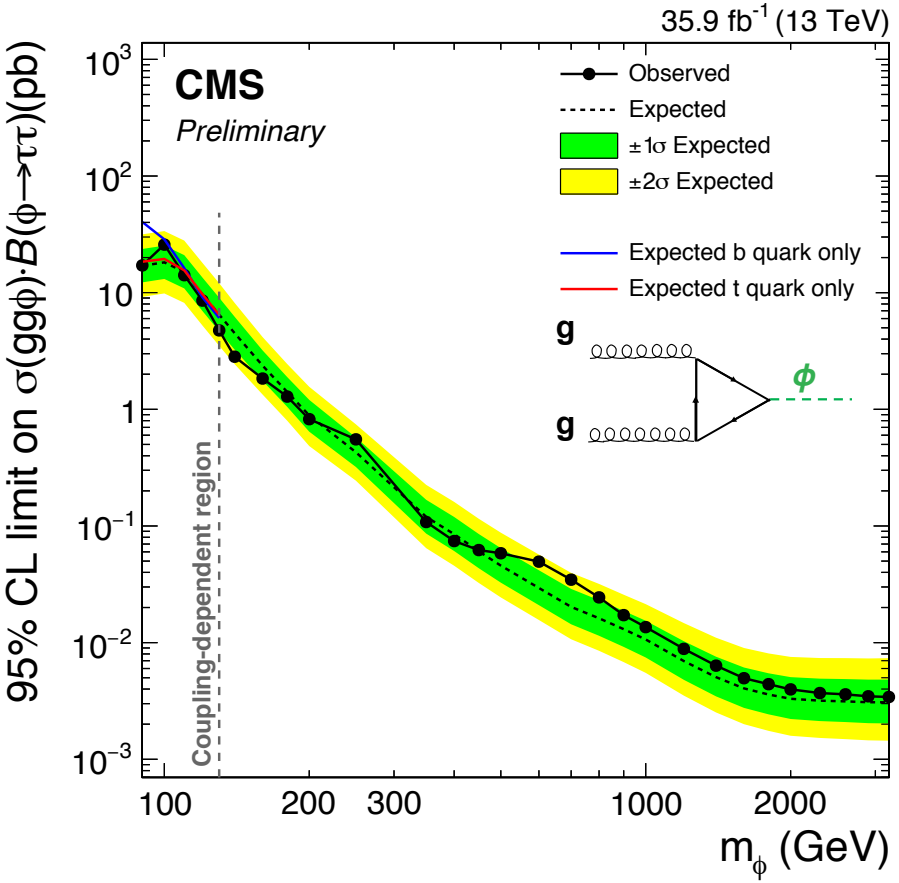
$$m_T^{tot} = \sqrt{m_T^2(E_T^{miss}, \tau_1^{vis}) + m_T^2(E_T^{miss}, \tau_2^{vis}) + m_T^2(\tau_1^{vis}, \tau_2^{vis})}$$

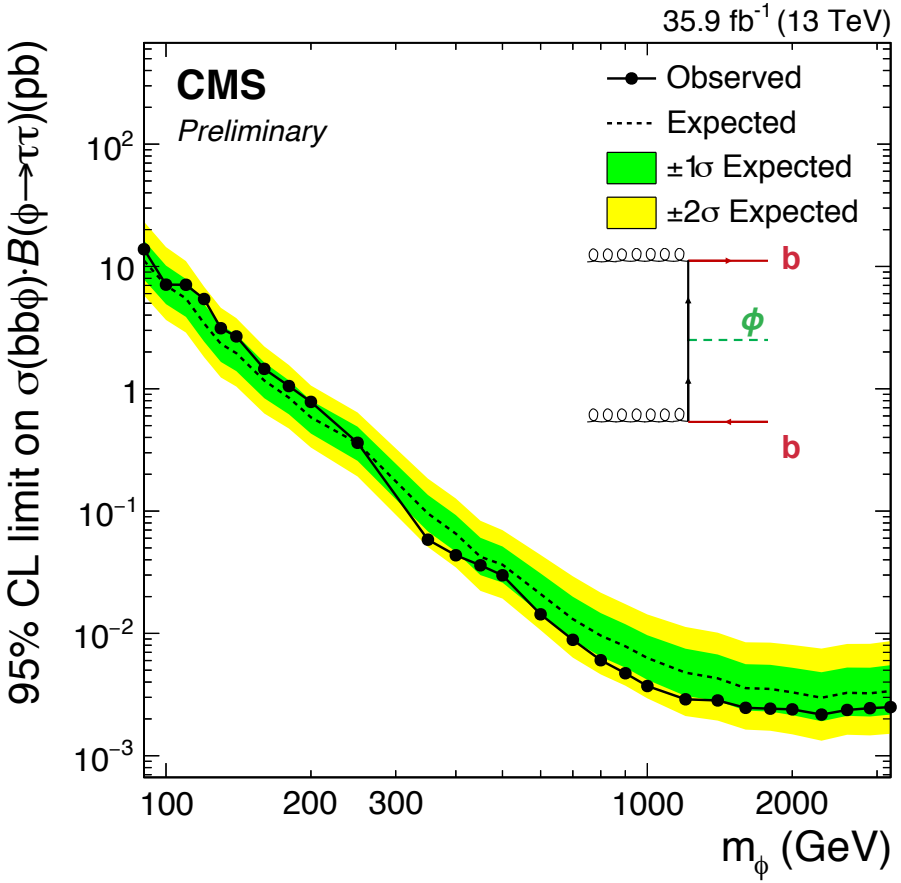
$$m_T(1,2) = \sqrt{2p_T(1)p_T(2) \cdot (1 - cos\Delta\phi(1,2))}$$



h/H/A→ττ: Analysis results

- **Model independent** exclusion limits for the **gg→ϕ** and **gg→bbϕ**
  - Combination of 4 channels in all categories
  - No significant excess

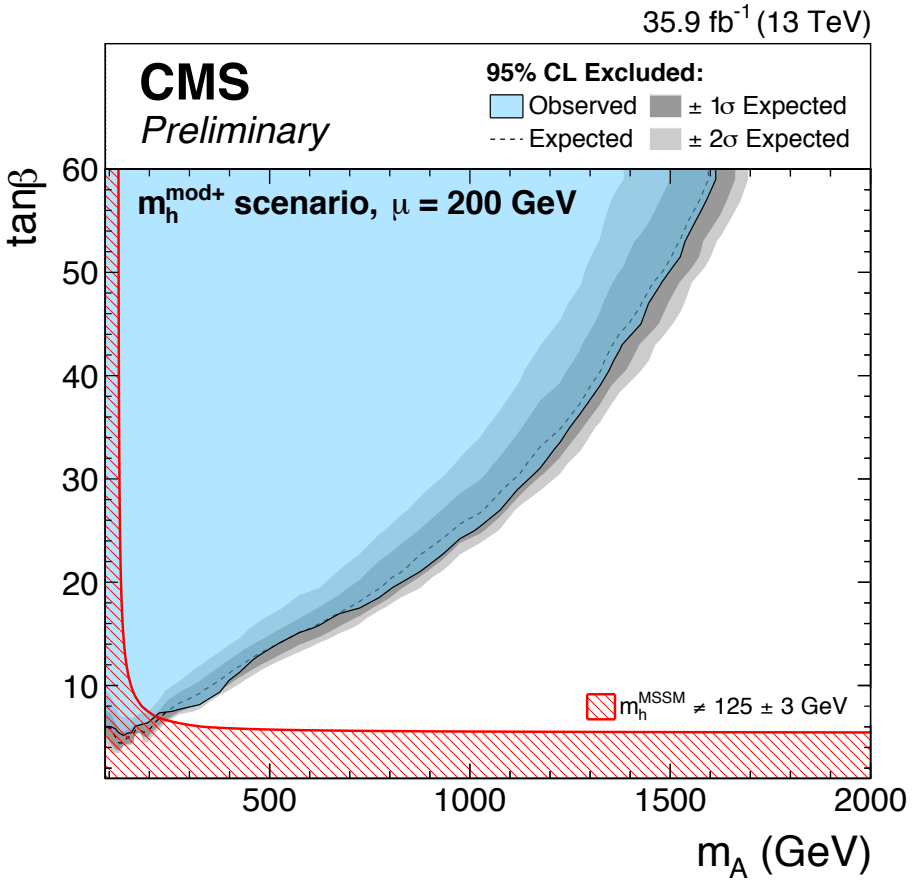


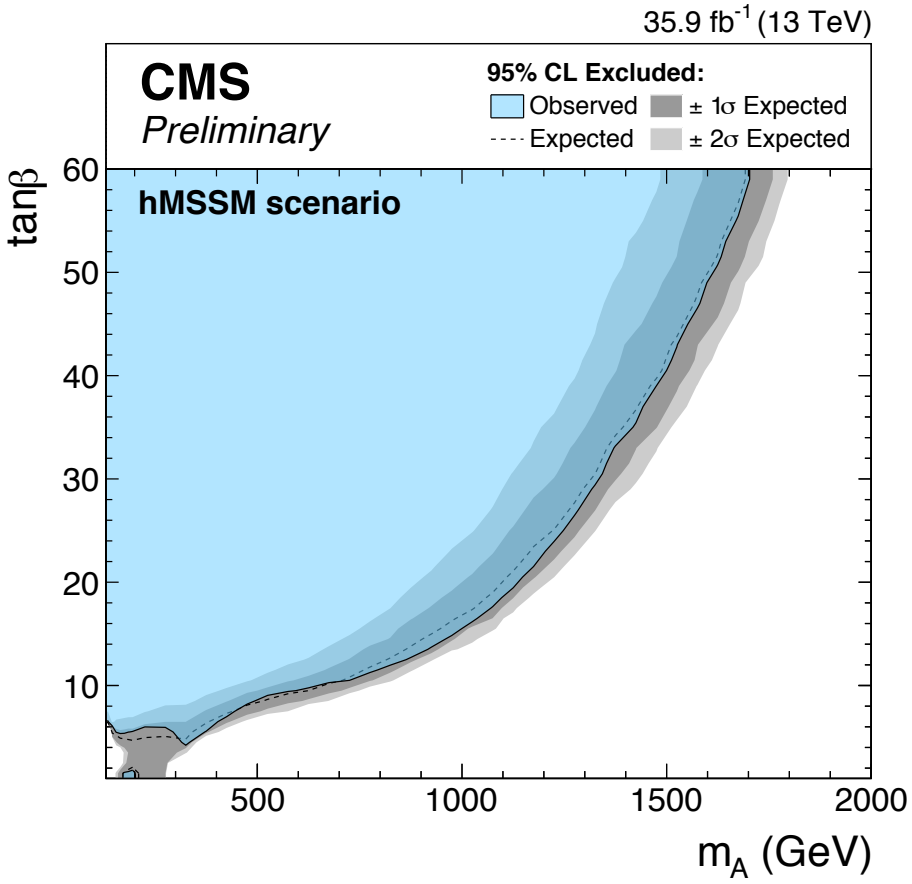


- Cover **large range** of m_ϕ

h/H/A→ττ: Results interpretation

- **Observed limits** interpreted within the m_h^{mod+} and **hMSSM** benchmark scenarios of **MSSM**



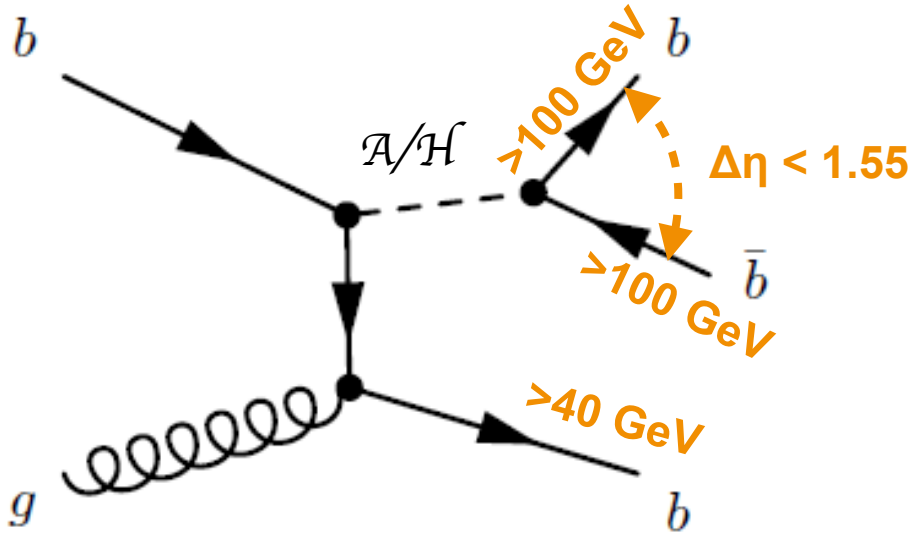


- Excluded region **down to tanβ ≳ 6 for $m_A \lesssim 250$** GeV and **up to $m_A \leq 1600$** GeV

High mass $b\bar{b}(H/A \rightarrow b\bar{b})$

CMS-PAS-HIG-16-018

- Search for the **b-associated** production of **degenerate H/A → $b\bar{b}$**
  - **Largest BR** in many MSSM and 2HDM scenarios
  - **+**
  - **Cross-section enhanced** up to factor ~ $2\tan^2\beta$;
- **Main challenge**: huge **QCD multi jet** production → **dedicated b-tag trigger** developed



- **Data-driven** QCD **background modelling**
- **Challenge**: **fit** of a **large mass range**
  - **Divide** large M_{12} range into **sub-ranges** to reduce the bias from the choice of the function and simplify the fitting
  - Functions developed in "**Reverse b-tag control region**"

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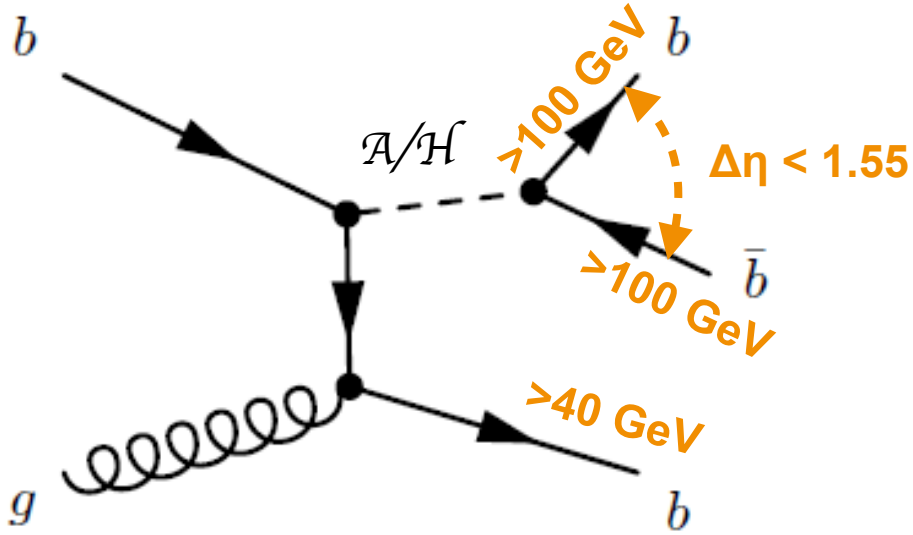

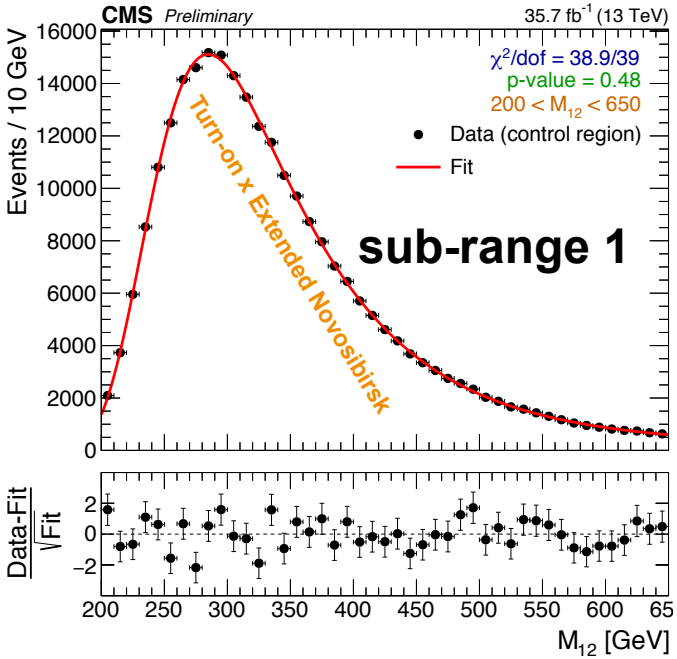

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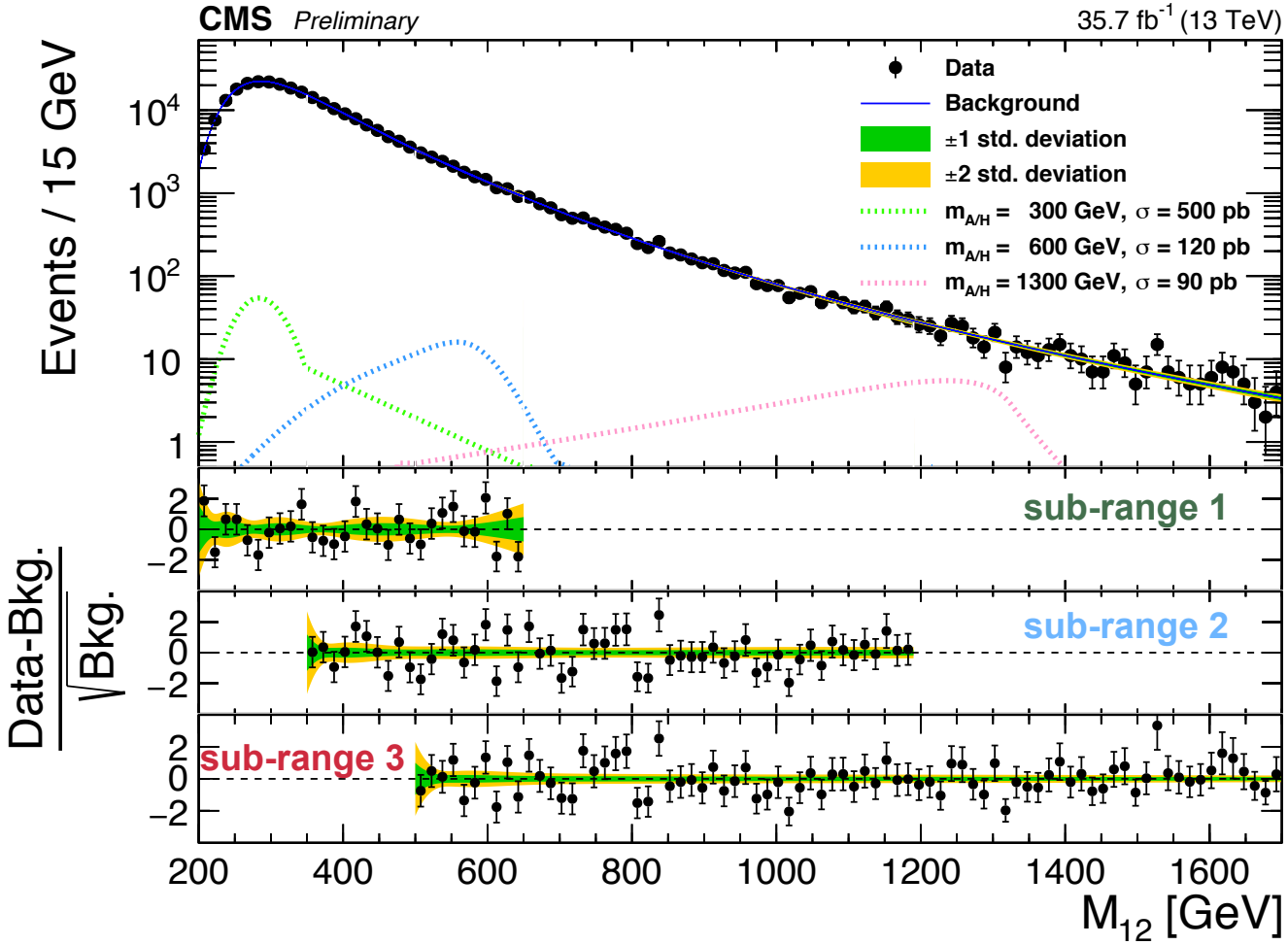
  - Functions developed in "**Reverse b-tag control region**"

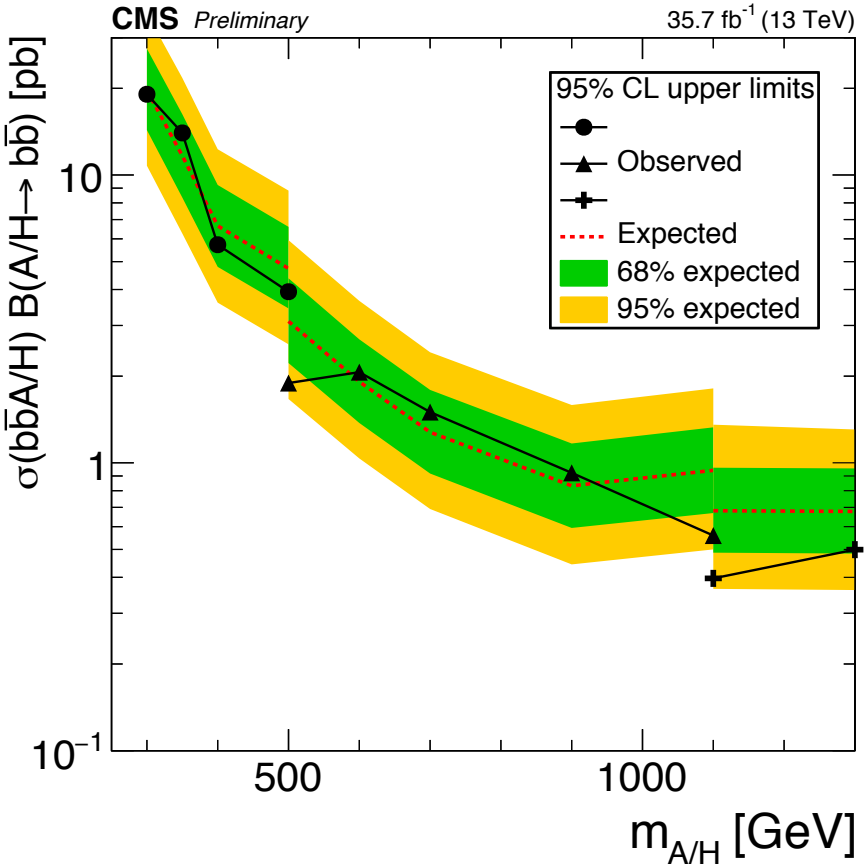
$b\bar{b}(H/A \to b\bar{b})$: Analysis features

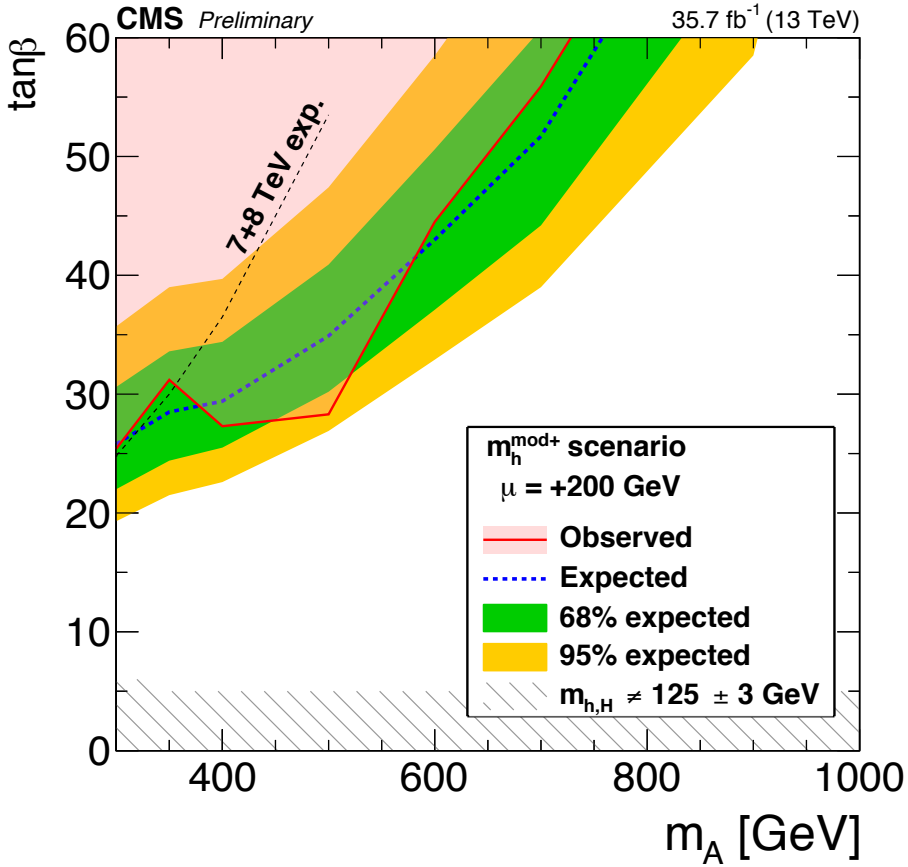
- Parameters of the background pdfs allowed to change between CR and SR
- **Data** is **well fitted** with functions validated in the CR
  - **No excess** found → compute **U**pper **L**imits



$b\bar{b}(H/A \to b\bar{b})$: Analysis results

- **Model independent exclusion limits** for the $b\bar{b}(H/A \to b\bar{b})$ cover **$m_{A/H}$ up to 1300 GeV**
- Translated into exclusion limits **on MSSM** parameters - **tanβ** and **M_A**



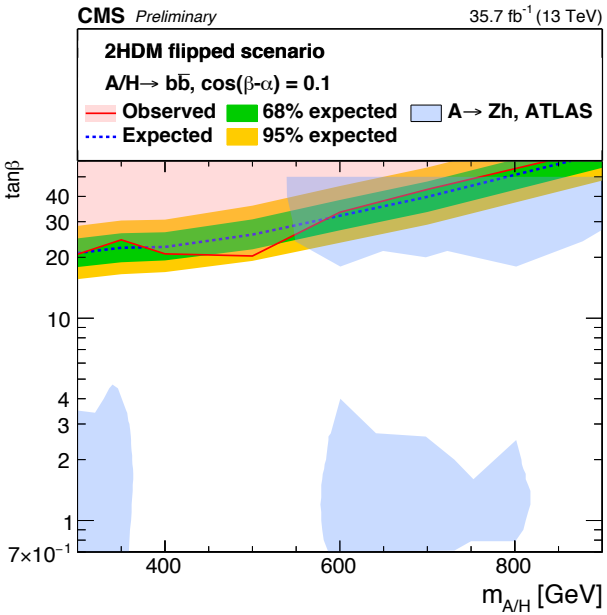


- Significant **improvement for m_h^{mod+}** scenario **wrt. Run-I** analysis, beyond 300 GeV

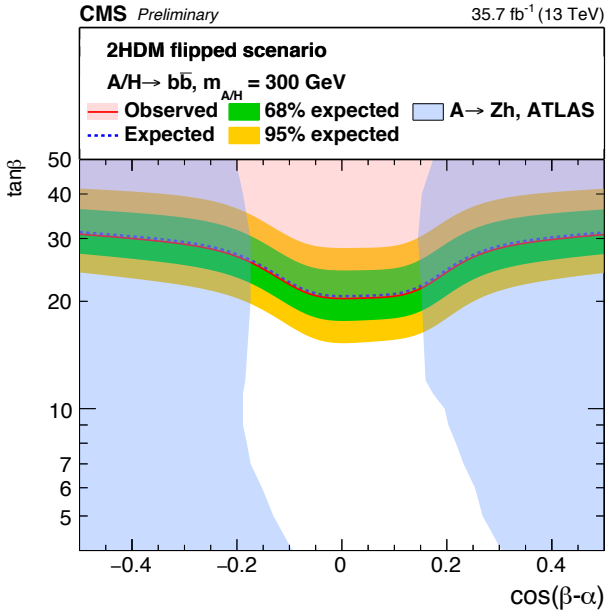
$b\bar{b}(H/A \to b\bar{b})$: Results interpretation

- **Exclusion limits** on **tanβ** vs **M_A** and **cos(β-α)** for 2HDM Flipped and Type-II* models
- h(125) measurements allow only small **|cos(β-α)|** (alignment limit):
  - **unique sensitivity** of this analysis

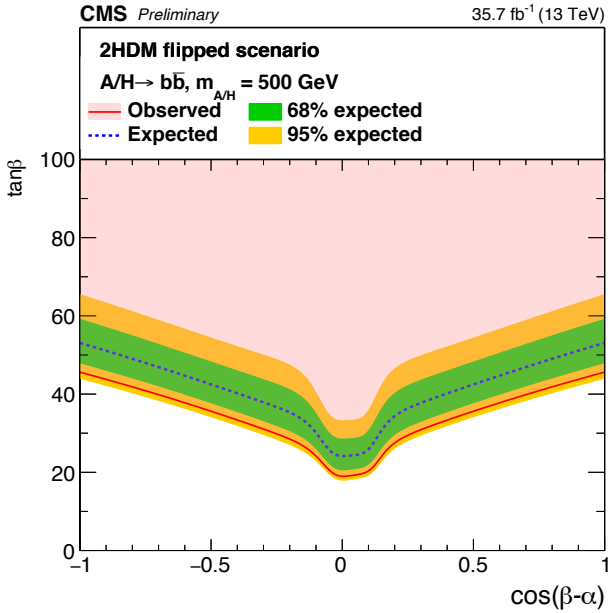
cos(β-α) = 0.1



M_A = 300 GeV



M_A = 500 GeV



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High mass X→ZZ

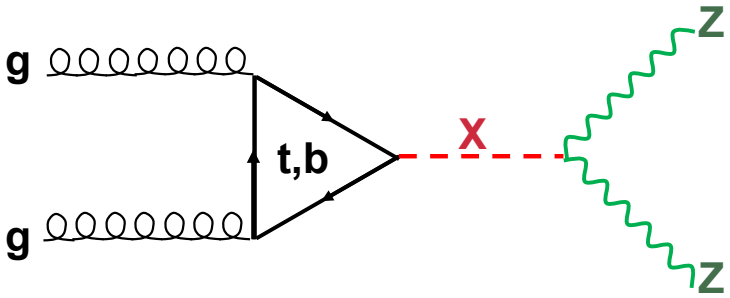
CMS-PAS-HIG-17-012

- Search for the spin-0 scalar **X→ZZ→4ℓ,2ℓ2q,2ℓ2ν**
  - **Clean** final state
  - **Manageable** backgrounds

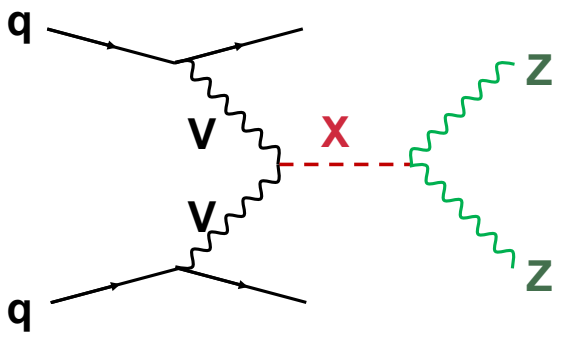
+

- **Established strategy** based on SM h(125) → ZZ analysis

- Consider 2 production mechanisms:
  - **gluon fusion**



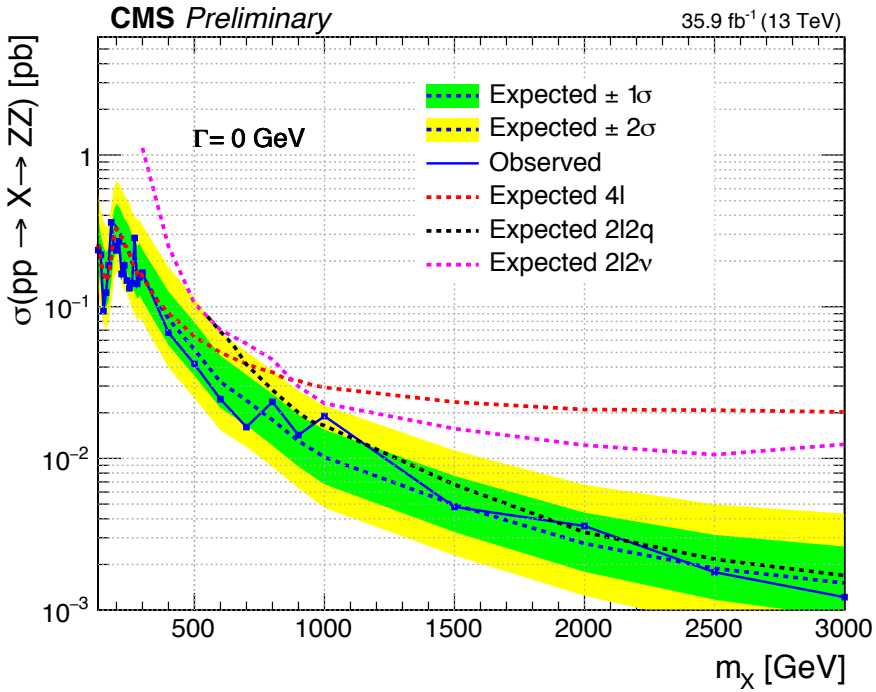
  - **electroweak**, dominated by VBF



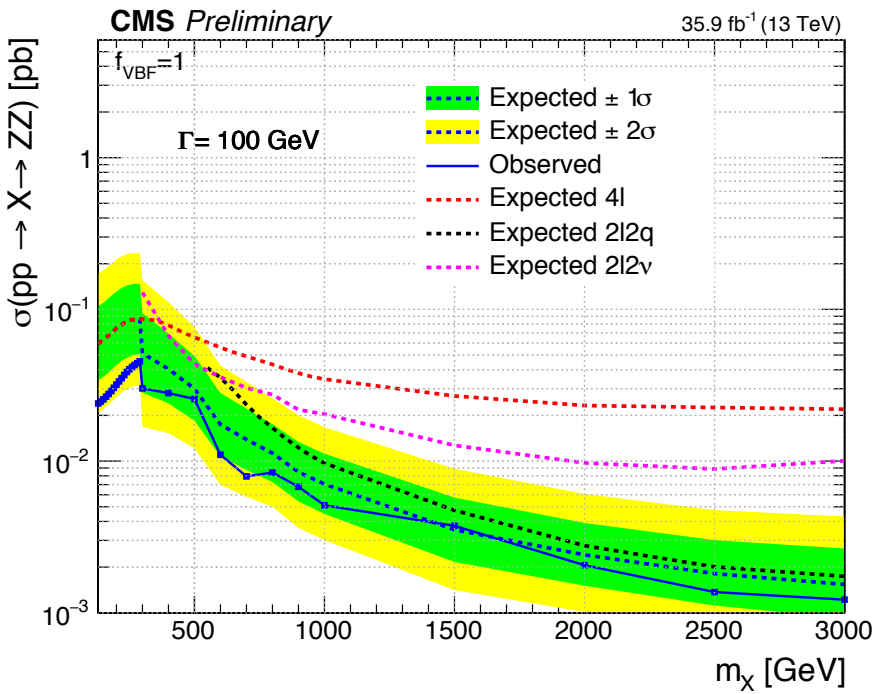
- Scanned parameters:
  - m_X - mass
  - Γ_X - width
  - f_{VBF} - EW/Total x-section
- Mass range: 130 GeV to 3 TeV

X→ZZ: Analysis results

f_{VBF} - free parameter; Γ_X = 0



f_{VBF} = 1; Γ_X = 100 GeV

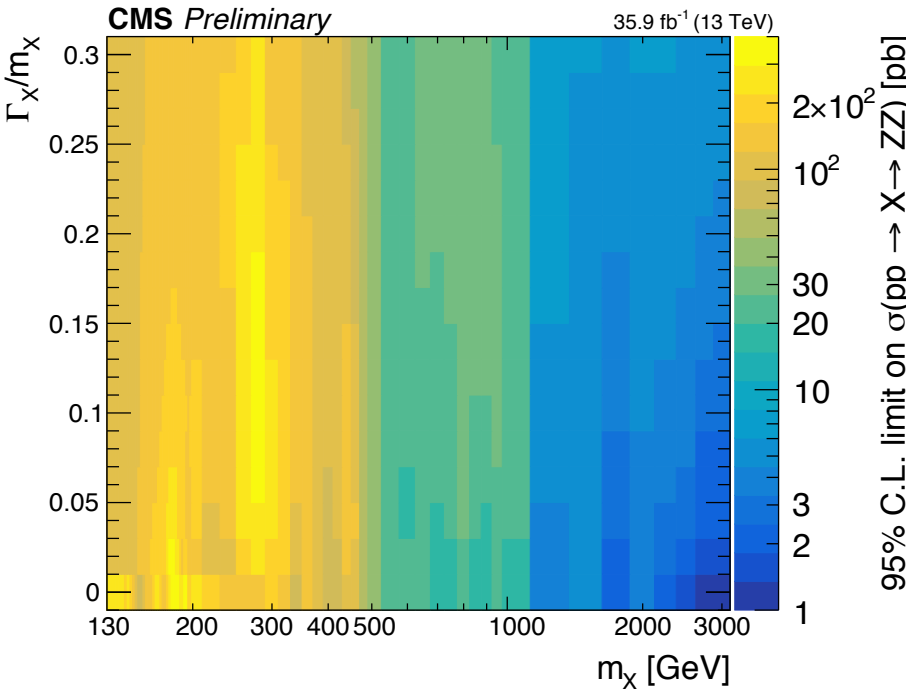


- **Upper Limits** on the **$\sigma_X \cdot B(X \to ZZ)$** as a function of m_X for different values of Γ_X and f_{VBF}
- More UL for different Γ_X and f_{VBF} available

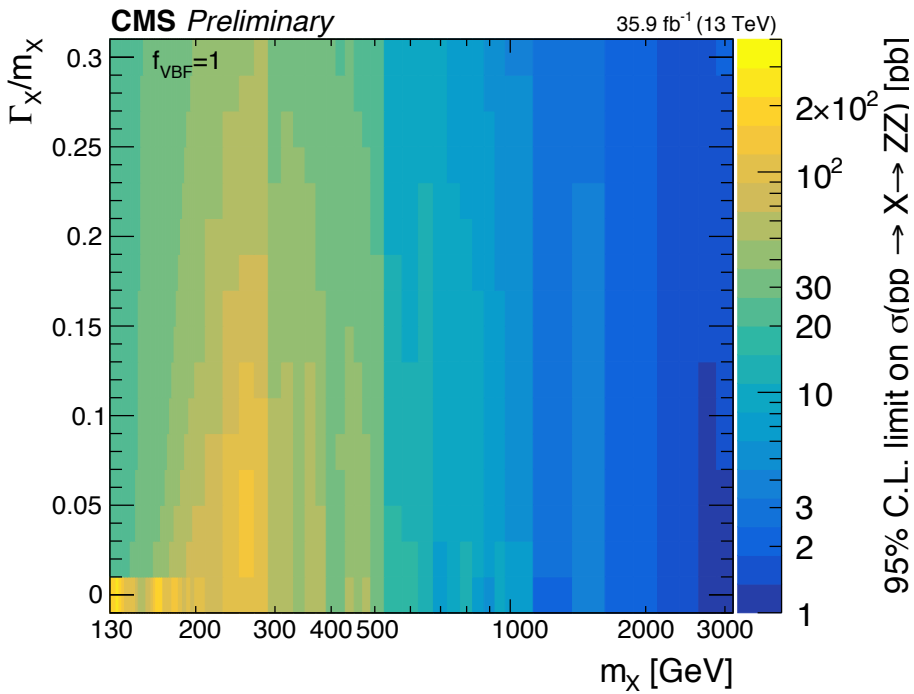
* - in the backup

X→ZZ: Analysis results

f_{VBF} - free parameter



f_{VBF} = 1



- **2D Observed Upper Limits** on the **$\sigma_X \cdot B(X \to ZZ)$** as a function of m_X and Γ_X/m_X
- Cover wide range of m_X and Γ_X/m_X

* - in the backup

Summary

- Searches for **additional Higgs** bosons presented
- **h/H/A→ττ analysis:** significant improvement compared to previous CMS analyses
  - exclude region of MSSM **down to tanβ ≳ 6 for $m_A \lesssim 250$** GeV and **up to $m_A \leq 1600$** GeV
- **bbH/A(→$b\bar{b}$) analysis**: unique at LHC
  - **improved** MSSM limits in m_h^{mod+}
  - strong **constraints** on the **«Flipped» 2HDM** scenario
- **X→ZZ analysis**: following the h(125) discovery strategy
  - **exclude** wide region of m_X from **130 GeV to 3 TeV** for **different Γ_X** and **production mechanisms** assumptions
- **Many more BSM Higgs** physics **results** still **to come** from full Run2 data

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Backup

Two Higgs Doublet Model (2HDM)

- Higgs sector structure and parameters:

$$\Phi_1 = \begin{pmatrix} w_1^+ \\ \frac{v_1+h_1+iz_1}{\sqrt{2}} \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} w_2^+ \\ \frac{v_2+h_2+iz_2}{\sqrt{2}} \end{pmatrix}$$

- Physical states: **8** - **3** = **5**

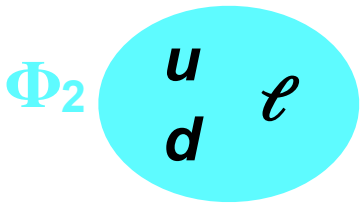
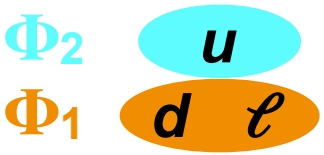
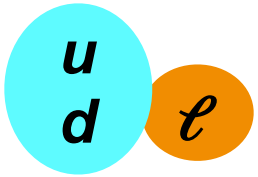
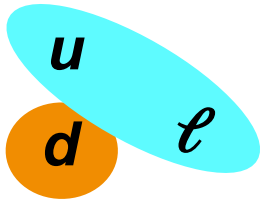
Goldstone bosons

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R(\alpha) \begin{pmatrix} H \\ h \end{pmatrix}, \begin{pmatrix} w_1^\pm \\ w_2^\pm \end{pmatrix} = R(\beta) \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}, \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = R(\beta) \begin{pmatrix} G^0 \\ A \end{pmatrix}$$

CP-even Charged CP-odd

- **tan β** - ratio of vacuum expectation values $tan\beta = \frac{v_2}{v_1}$
- **α** - **mixing** angle between h and H $R(\alpha) = \begin{pmatrix} cos\alpha & -sin\alpha \\ sin\alpha & cos\alpha \end{pmatrix}$

- **4 types of 2HDM** with natural flavour and CP conservation, depending on how the 2 Higgs doublet fields couple to SM particles

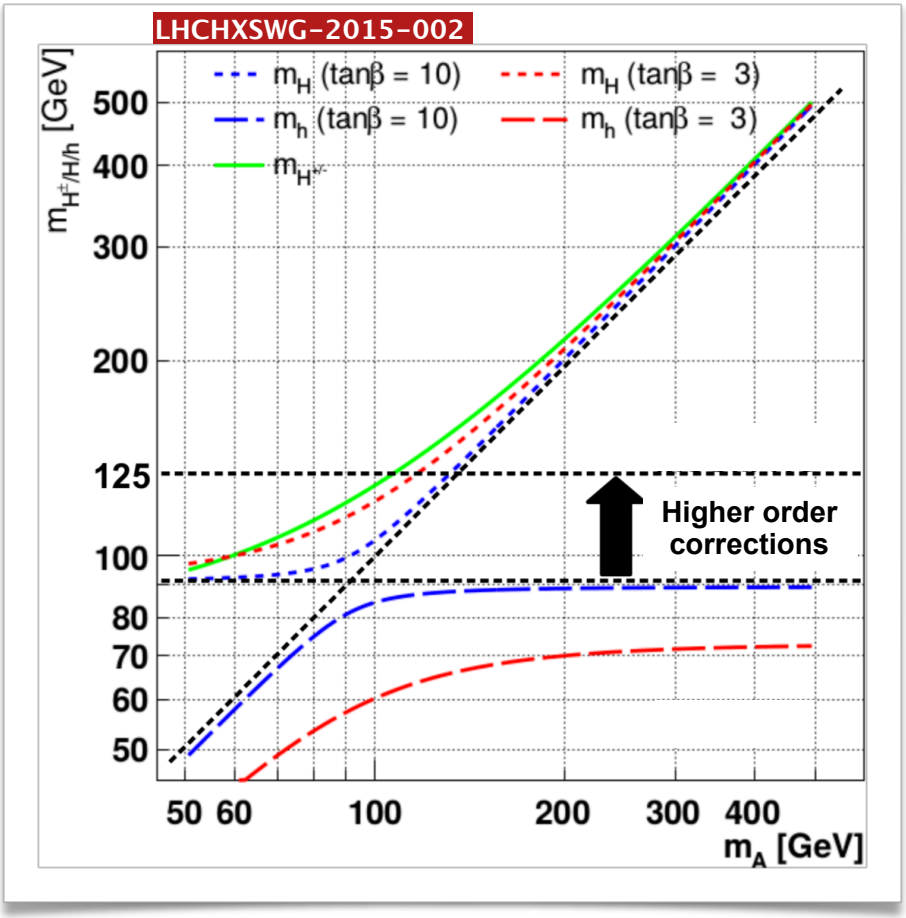
Type I	Type II	Lepton Specific	Flipped
			
all fermion couples to one Higgs boson	up v.s. down	quark v.s. lepton	

u - (u,c,t)
d - (d,s,b)
ℓ - (e,μ,τ)

Minimal Supersymmetric Standard Model (MSSM)

- Features Higgs sector as in 2HDM Type-II.
  - **Two parameters at tree-level:**
    m_A and tanβ

$$m^2_{H^\pm} = m^2_A + m^2_W$$
$$m^2_{H,h} = \frac{1}{2}(m^2_A + m^2_Z \pm \sqrt{(m^2_A + m^2_Z)^2 - 4m^2_A m^2_Z cos^2 2\beta})$$
$$tan\alpha = \frac{-(m^2_A + m^2_Z) sin2\beta}{(m^2_Z - m^2_A)cos2\beta + \sqrt{(m^2_A + m^2_Z)^2 - 4m^2_A m^2_Z cos^2 2\beta}}$$



- MSSM **features:**
  - Solve **hierarchy** problem
  - introduce **dark-matter candidate**
- **Compatibility with h(125)** achieved by the HO corrections:
  - **m_h increased** up to 30%
- Variety of **benchmark scenarios** to test different phase-space properties:
  - m_h^{mod+}, hMSSM…

MSSM h/H/A→ττ

CMS-PAS-HIG-17-020

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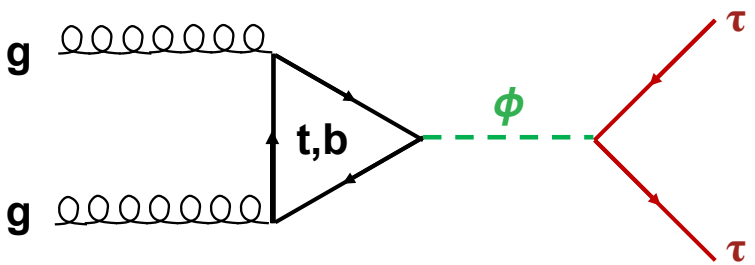
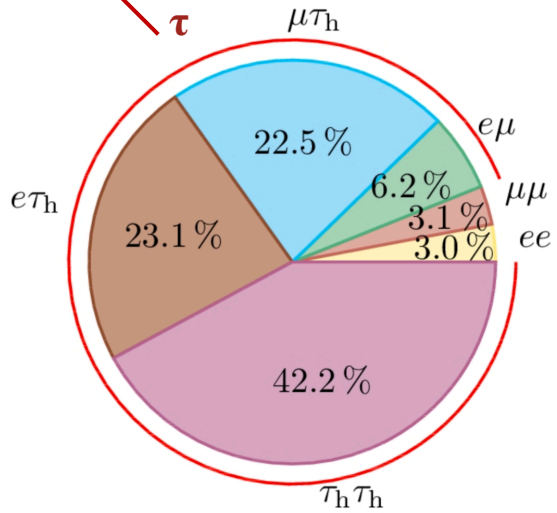
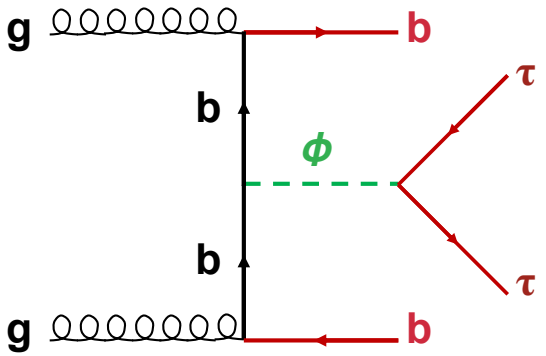


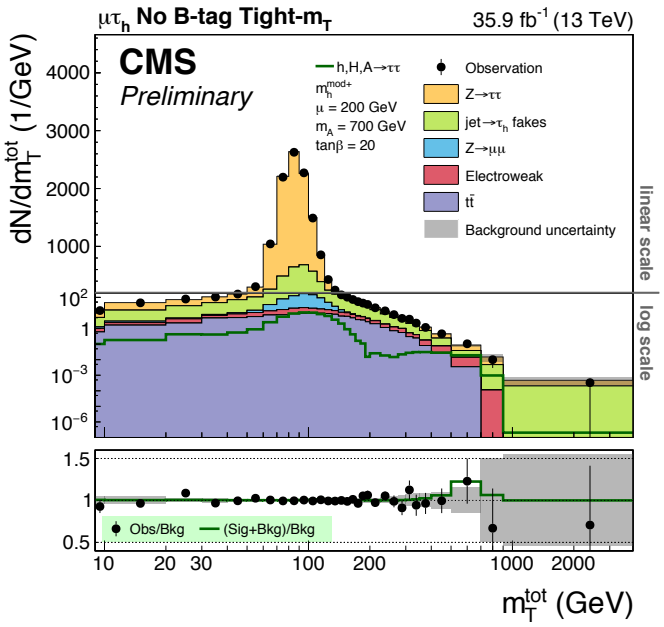


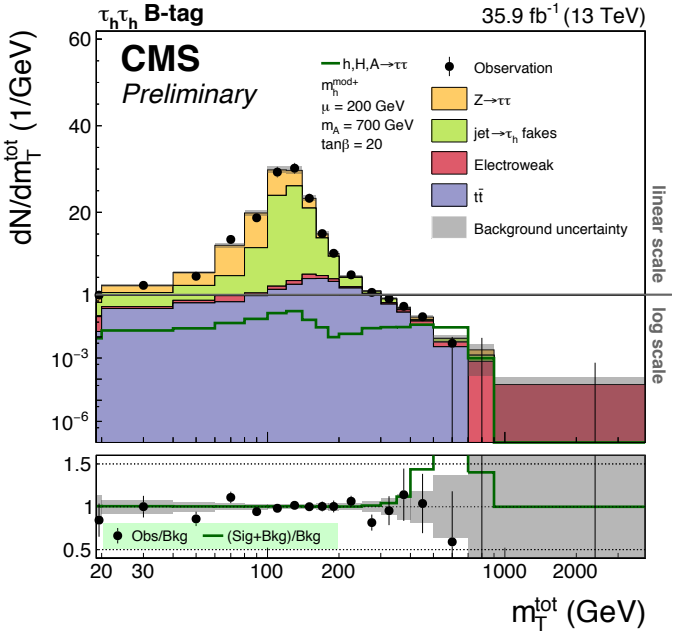


h/H/A→ττ: Analysis features

- **16 categorise** to optimise sensitivity:
  - **eμ**: $D_\zeta = p_\zeta^{miss} - 0,85 p_\zeta^{vis}; \quad p_\zeta^{miss} = \vec{p}_T^{\,miss} \cdot \zeta; \quad p_\zeta^{vis} = (\vec{p}_T^{\,e} + \vec{p}_T^{\,\mu}) \cdot \zeta$
  - **e/μ τ_h**: $m_T(1,2) = \sqrt{2 p_T(1) p_T(2) \cdot (1 - cos\Delta\phi(1,2))}$
  - **all** : B-tag / No B-tag
- Largely **data-driven background** estimation
- **Signal extraction observable**:

$$m_T^{tot} = \sqrt{m_T^2(E_T^{miss}, \tau_1^{vis}) + m_T^2(E_T^{miss}, \tau_2^{vis}) + m_T^2(\tau_1^{vis}, \tau_2^{vis})}$$





h/H/A→ττ: Validation of background estimation techniques

- **Background estimation** methods extensively **checked:**
  - Fake Factor method is checked using **MC simulation**
  - Z→ττ is checked using the **τ-embedding** method

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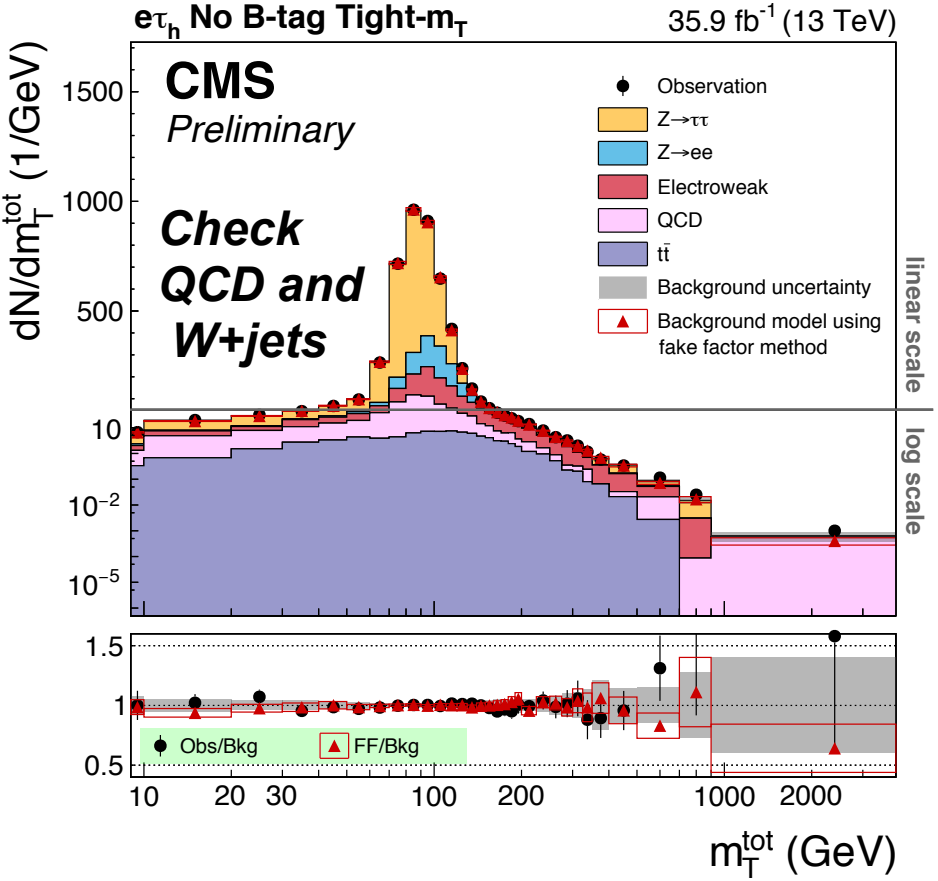
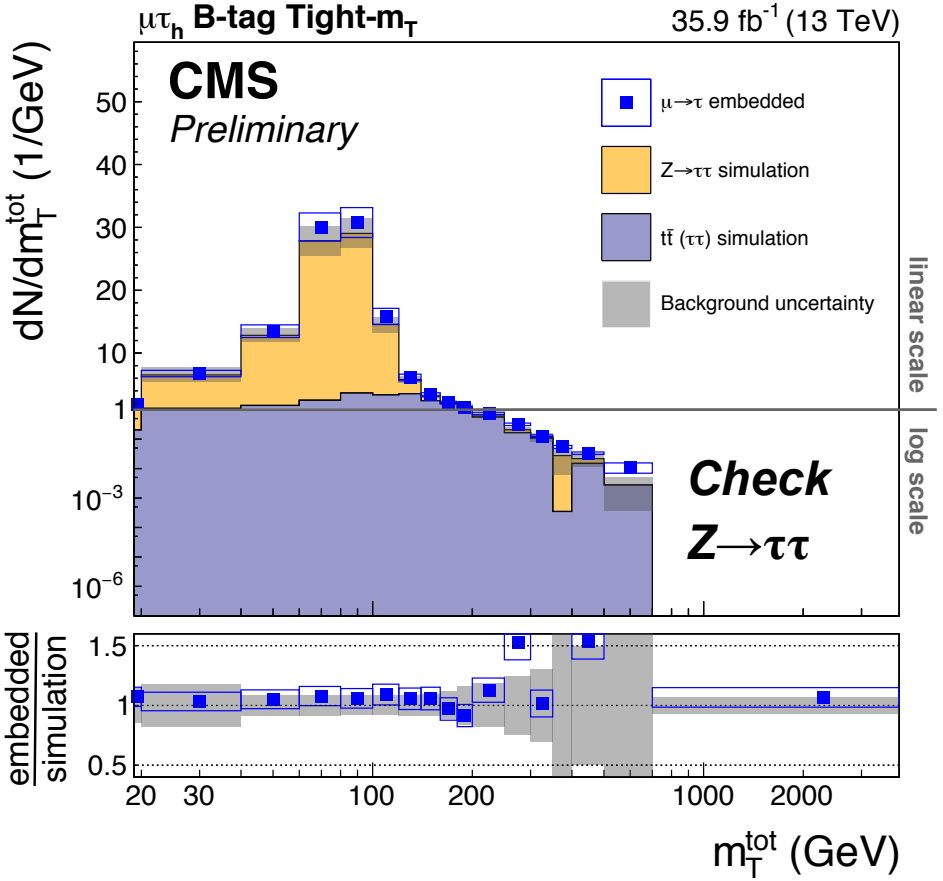
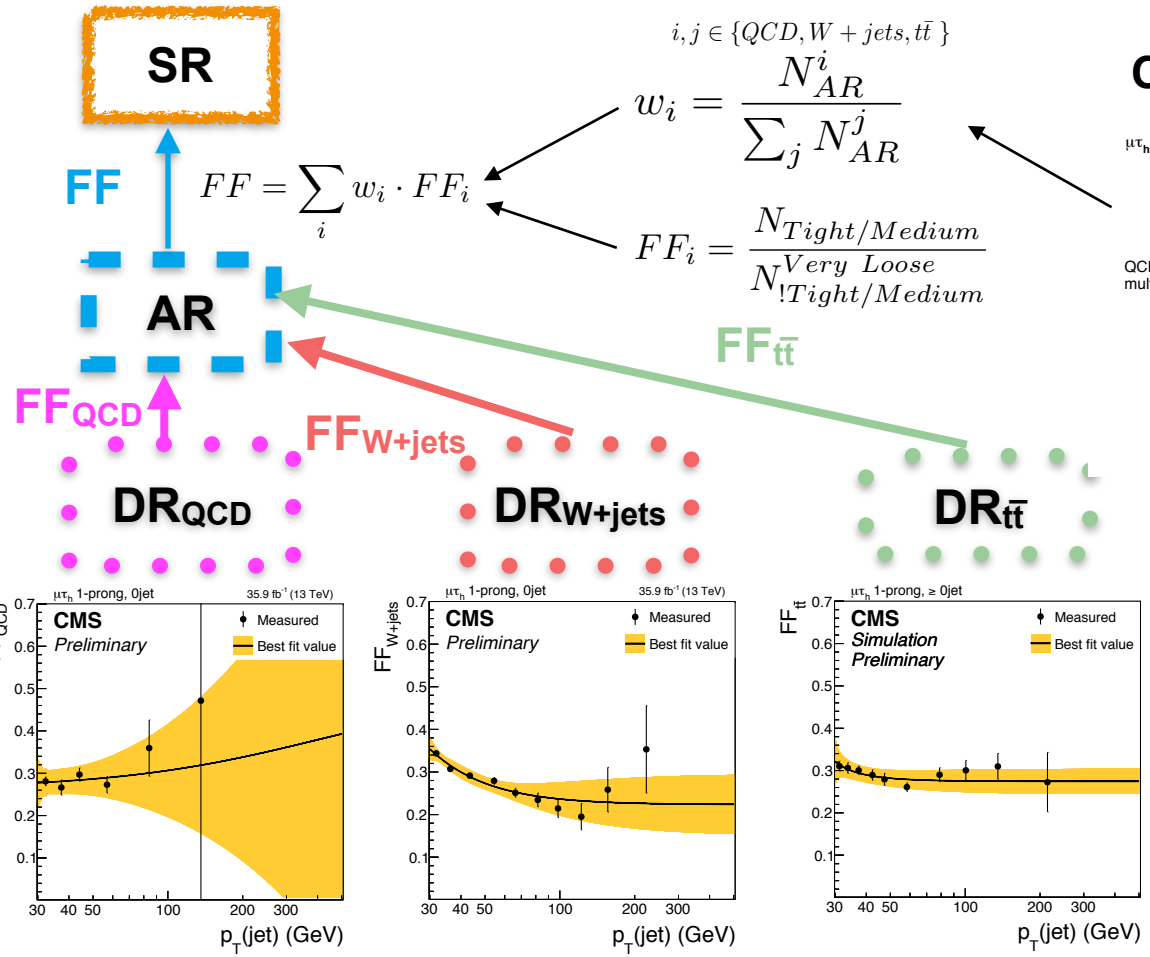
  - Fake Factor method is checked using **MC simulation**
  - Z→ττ is checked using the **τ-embedding** method

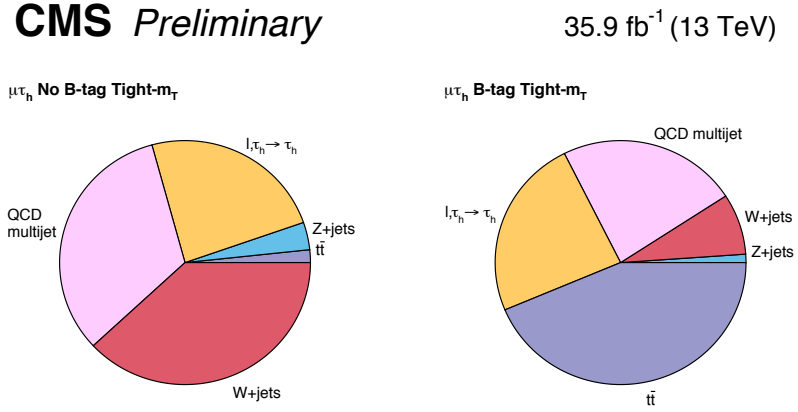


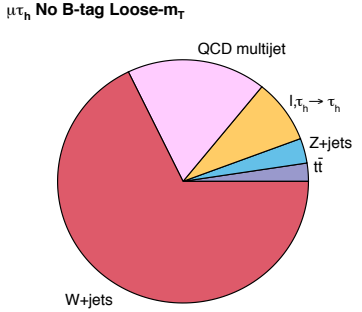


h/H/A→ττ: Fake Factor (FF) method

- **jet→τ_h misidentification** background **estimation** based on anti-isolated *Application Region (AR)*:
  - τ_h identification: **Tight**(Medium) → Very **Loose**







h/H/A→ττ: Signal Modeling for Gluon-Fusion

- **Decompose cross-section** into t-only, b-only and interference term

$$\sigma^{\text{tot}}_{\text{MSSM}} \propto \left| \; \text{(g g → b → h, H, A)} + \text{(g g → t → h, H, A)} \; \right|^2$$

$$= \sigma^{\text{t}}_{\text{MSSM}}\left(Q_{\text{t}}\right) + \sigma^{\text{b}}_{\text{MSSM}}\left(Q_{\text{b}}\right)$$

$$+ \left(\sigma^{\text{t+b}}_{\text{MSSM}}\left(Q_{\text{tb}}\right) - \sigma^{\text{t}}_{\text{MSSM}}\left(Q_{\text{tb}}\right) - \sigma^{\text{b}}_{\text{MSSM}}\left(Q_{\text{tb}}\right)\right)$$

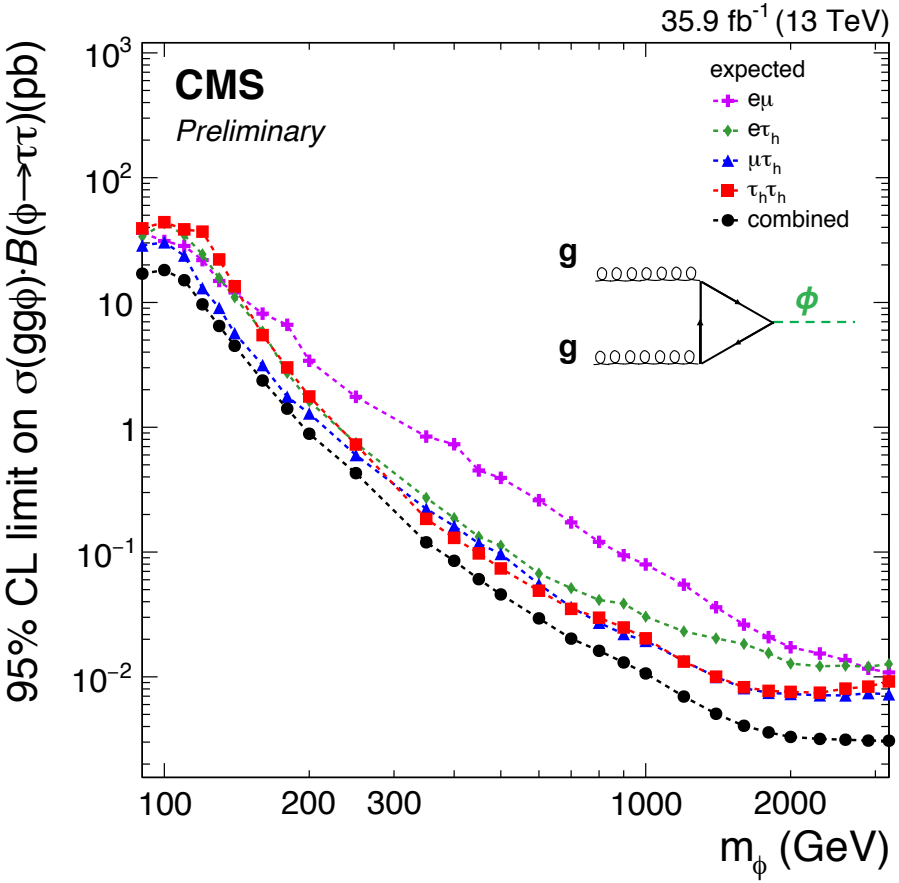
$\times Y_{\text{t}}^2$ → t quark alone

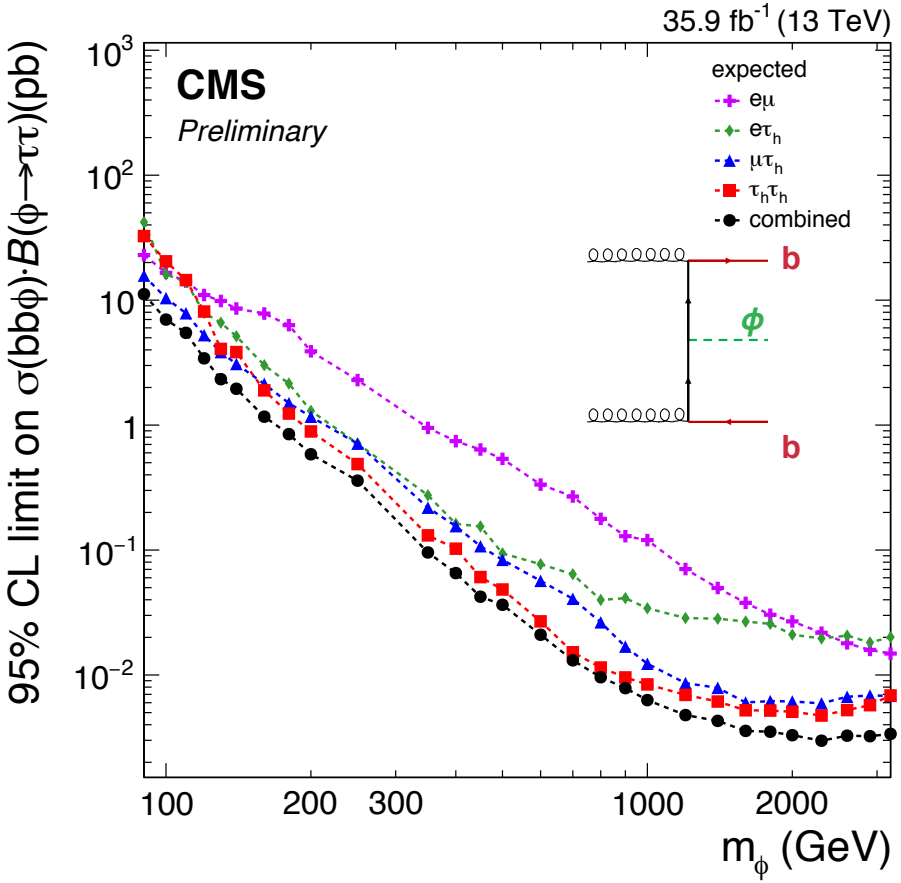
$\times Y_{\text{t}}\, Y_{\text{b}}$ → tb-interference

$\times Y_{\text{b}}^2$ → b quark alone

h/H/A→ττ: Analysis results

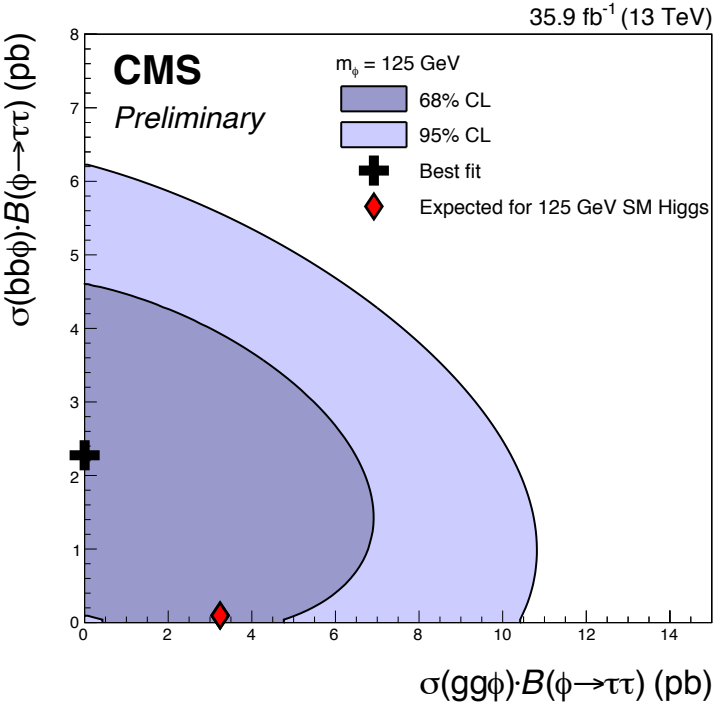
- **Model independent expected** exclusion limits for the $gg \to \phi$ and $gg \to bb\phi$
  - Show sensitivity channel-by-channel



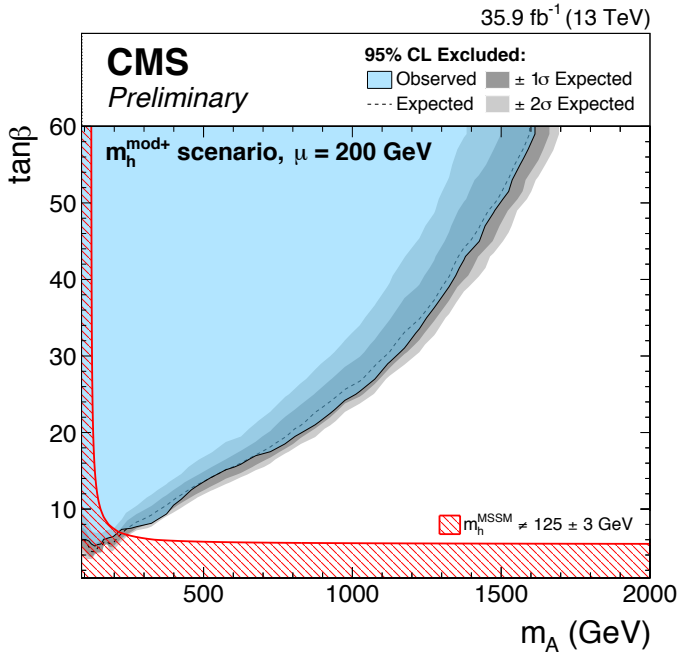


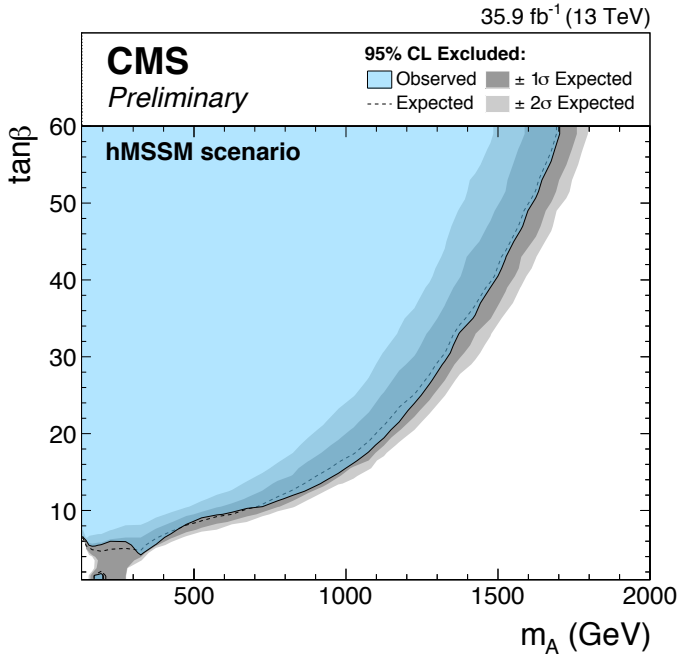
h/H/A→ττ: Results interpretation

- **Observed limits** interpreted within the m_h^{mod+} and **hMSSM** benchmark scenarios of **MSSM**
  - Explored region **down to tanβ ≳ 6 for $m_A \lesssim$ 250** GeV and **up to $m_A \leq$ 1600** GeV



- Model independent **2D likelihood scans** for 28 mass points
  - allow **re-interpretation** in alternative/new models

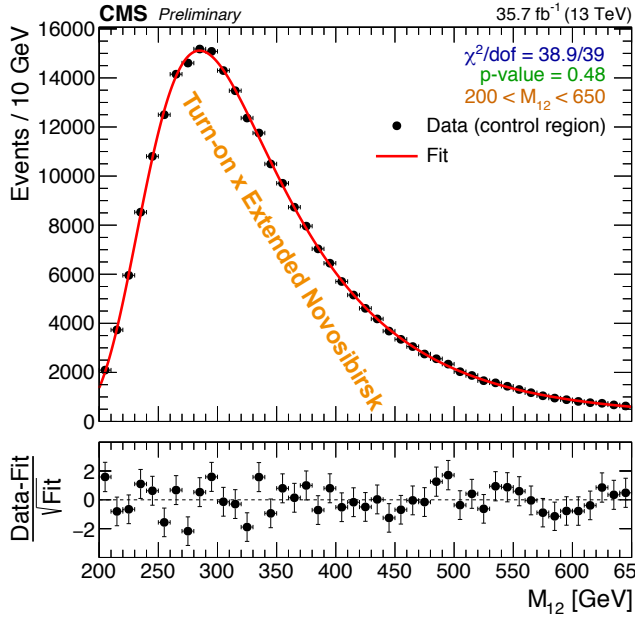


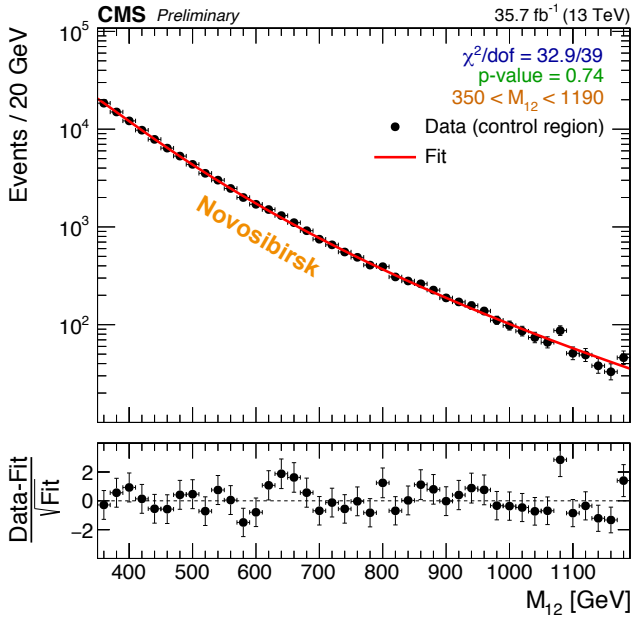


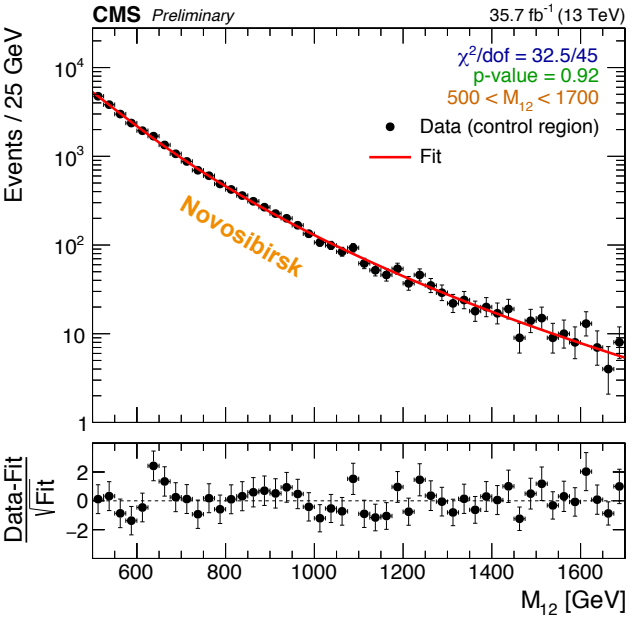
$b\bar{b}(H/A \to b\bar{b})$: Analysis features

- **Data-driven** QCD **background modelling** using analytical functions
- Main **challenge**: **precise fit** of a **large mass range** including the **background peak region**
  - **Divide** large M_{12} range into **sub-ranges** to reduce the bias from the choice of the function and simplify the fitting
  - Functions developed in "**Reverse b-tag control region**"

sub-range 1 **sub-range 2** **sub-range 3**



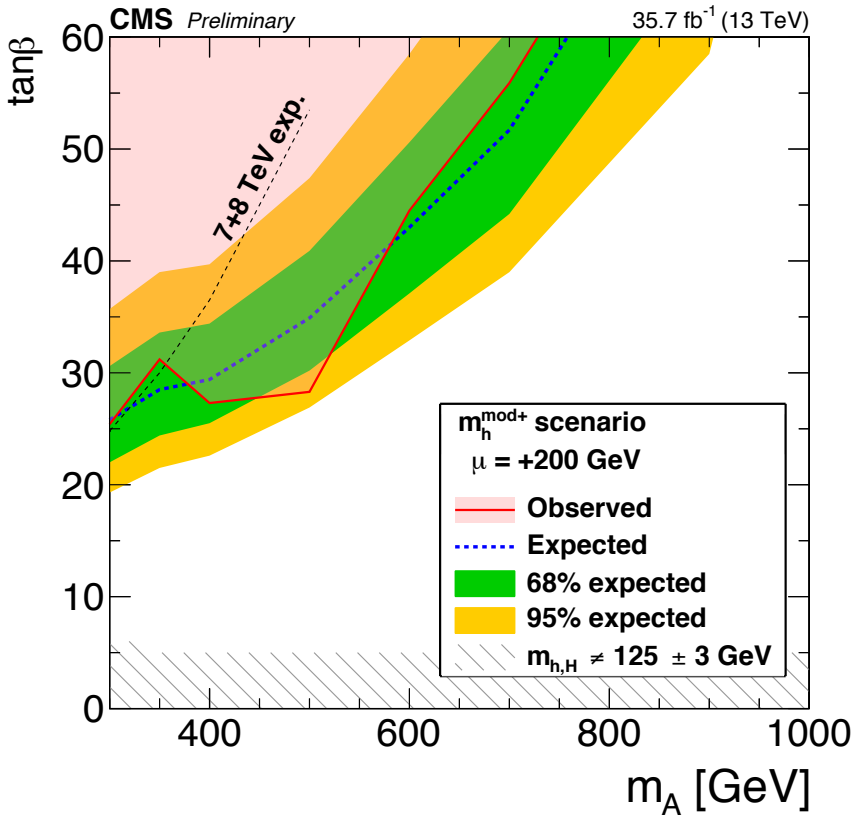


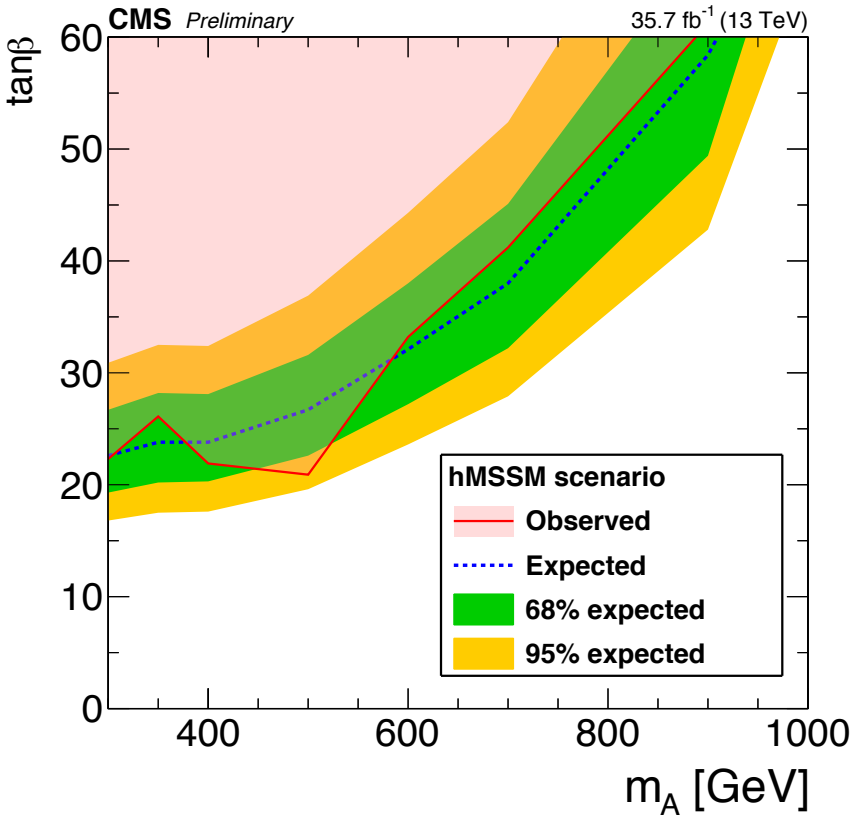


- Functions from **control region** translated to the **signal region**

$b\bar{b}(H/A \to b\bar{b})$: Results interpretation

- Observed **limits** are translated into exclusion limits **on MSSM** parameters - **tanβ** and **M_A**
- Interpretation within the **m_h^{mod+}** and **hMSSM** benchmark scenarios*.



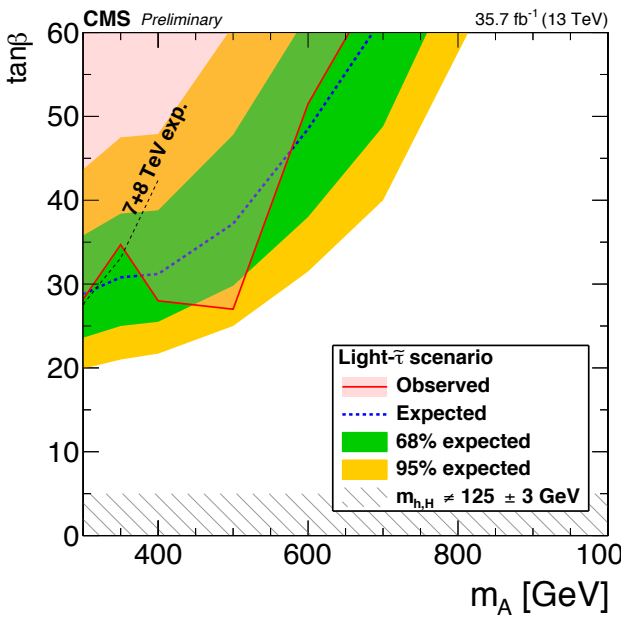


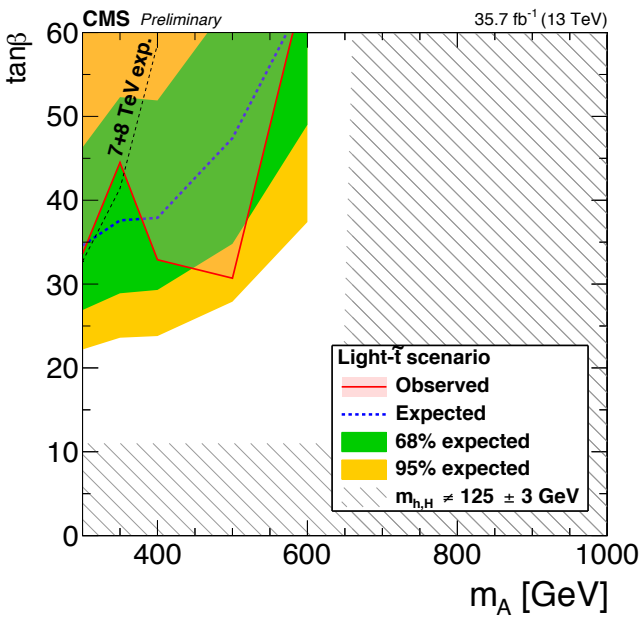
- Significant **improvement for m_h^{mod+}** scenario **wrt. Run-I** analysis, beyond 300 GeV
- hMSSM interpretation: lower tanβ limits than m_h^{mod+} at large M_A

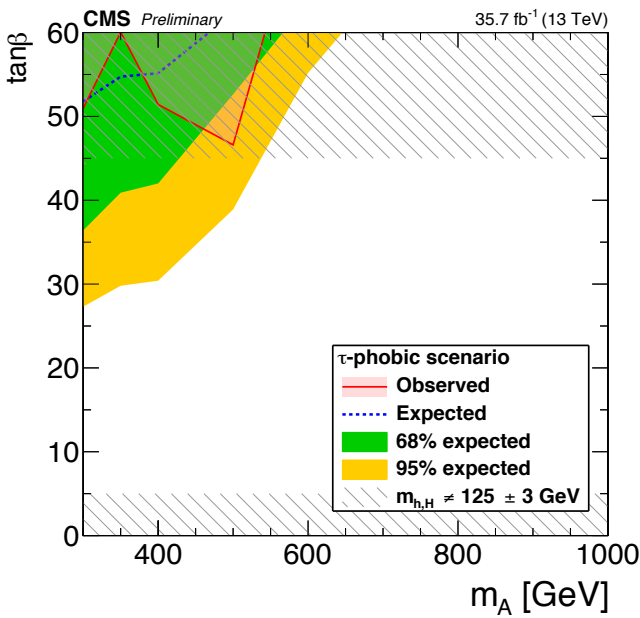
* - more scenarios in the backup

$b\bar{b}H/A \to b\bar{b}$: Results interpretation

- Expected **limits** are translated into exclusion limits **on MSSM** parameters - **tanβ** and **M_A**
- Interpretation performed using **NNLO** cross sections in the **Santander** matching within the **light-$\tilde{\tau}$** ,**light-$\tilde{t}$** and **τ-phobic** benchmark scenarios





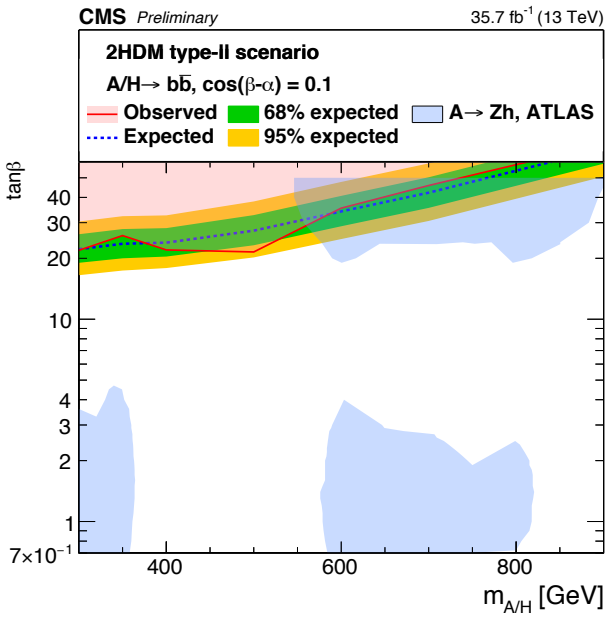


- 13 TeV limits are better than at 7 + 8 TeV

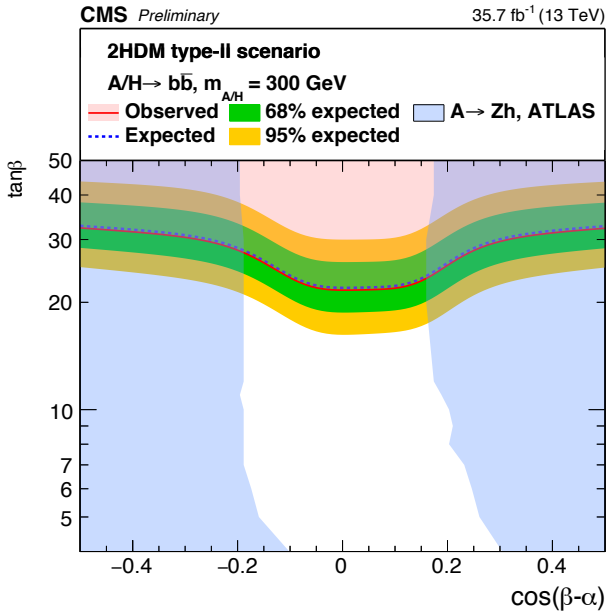
$b\bar{b}H/A \to b\bar{b}$: Results interpretation

- **Exclusion limits** on **tanβ** vs **M_A** and **cos(β-α)** for 2HDM Type-II model
- **Uniquely sensitive** measurements for small **|cos(β-α)|** (alignment limit) for **high** values of **tanβ**:
  - where couplings are compatible to h(125) measurements

cos(β-α) = 0.1



M_A = 300 GeV



M_A = 500 GeV